Lessons from two field tests on pipeline damage detection using acceleration measurement (Invited Paper)

Masanobu Shinozuka [*a], Sungchil Lee[a], Sehwan Kim[a], and Pai H. Chou[a]
[a]University of California, Irvine, CA USA 92697-2700

ABSTRACT

Early detection of pipeline damages has been highlighted in water supply industry. Water pressure change in pipeline due to a sudden rupture causes pipe to vibrate and the pressure change propagates through the pipeline. From the measurement of pipe vibration the rupture can be detected. In this paper, the field test results and observations are provided for implementing next generation of SCADA system for pipeline rupture detection. Two field tests were performed on real buried plastic and metal pipelines for rupture detection. The rupture was simulated by introducing sudden water pressure drop caused by water blow-off and valve control. The measured acceleration data at the pipe surfaces were analyzed in both time and frequency domain. In time domain, the sudden narrow increase of acceleration amplitude was used as an indication of rupture event. For the frequency domain analysis, correlation function and the short time Fourier Transform technique were adopted to trace the dominant frequency shift. The success of rupture detection was found to be dependent on several factors. From the frequency analysis, the dominant frequency of metal water pipe was shifted by the water pressure drop, however, it was hard to identify from the plastic pipeline. Also the influence of existing facility such as airvac on pipe vibrations was observed. Finally, several critical lessons learned in the viewpoint of field measurement are discussed in this paper.

Keywords: Pipeline, damage detection, acceleration measurement, correlation function

1. INTRODUCTION

Vibration or acoustic signal measurement of water pipe to detect and locate damage or water leaks has been adopted in many research[1, 2]. The most widely used method for locating rupture is based on the correlation technique[3]. The technique is very straightforward. In this method a rupture or water leak acts as a signal source and two sensors as receivers. The delay time between two signals at the sensors attached on a pipeline network, computed from the cross correlation function, is used for locating water leak[3-5]. To enhance the detection performance signal processing techniques such as filtering and windowing are adopted during the procedure. In this method the signals are assumed to be stationary[5]. Though many correlation based techniques are widely used and reported to be successful to locate water leaks, several limits should be overcome to be applied to water supply systems which have a lot of water flow control units and may generate non-stationary flow and unexpected water flow changes. Moreover, the techniques should be verified for water pipe with large or varying diameters.

In this paper, a more simple but robust method to detect rupture was applied to real water pipe with large diameter for the next generation of SCADA system. The fundamental idea of the new method is that change in water pressure induced by rupture produces a sharp peak in acceleration signal. So rupture can be identified directly from acceleration signal. To verify the new proposed method, it is applied to real buried plastic and metal pipes with large diameters.

2. DESCRIPTION OF FIELD TESTS

2.1 PVC pipe test

A field test to verify the proposed method was performed by UC Irvine (UCI) and Santa Ana Watershed Project Authority (SAWPA) on May 17, 2010. The water pressure change was introduced by blowoff. From the several candidate locations, as seen in Figure 1, AV 0340 and BO 0335 were selected for the measurement and blowoff sites.

[*] Further author information: (Send correspondence to Masanobu Shinozuka)
E-mail: shino@uci.edu; phone +1 949 824 9379

The blowoff was carried out at BO 0335 location and the pipe vibration due to the blowoff was recorded at AV 0340 location. The distance between two locations is about 71 m (233 ft). Figure 2 shows the manholes at the two locations. The blowoff location (BO 0335) is located on the traffic road and the water blown off was gushed into the water tank truck as shown in Figure 3. The piezoelectric sensors having a sensitivity of 500mV/g were installed on the PVC pipe at AV 0340 location. The pipe is 60.96 cm (24 in) diameter with thickness of 1.22 cm (0.48 in). The pipe vibration signals were recorded by an oscilloscope for piezoelectric sensors as shown in Figure 4. Due to the unavailability of the electric power, a portable power generator was used for the power supply to the data recording systems.

The piezoelectric accelerometers were installed before and after an existing airvac to see the effect of it on the pipe dynamic responses. The sensor 1 (channel 1) in Figure 5 was installed on the far side from the blowoff location. Water flows from AV 0340 to BO 0335 (i.e. channel 1 to channel 2).

Table 1 summarizes the blowoff test procedure. Before starting the blowoff, the pipe vibration had been recorded for 650 seconds under normal traffic condition. The vibration characteristics of this period were assumed as baseline. The blowoff was continued for 510 seconds and the pipe vibration was recorded again for 355 seconds after the end of blowoff. The sampling frequency was 1.25 kHz.

Table 1. Blowoff test procedure

Flow state	Time (sec)	Description
Normal flow	0-650	-
Start of blow off	650	-
End of blow off	1,160	-
End of test	1,515	Total elapsed time : 25 min. 25 sec

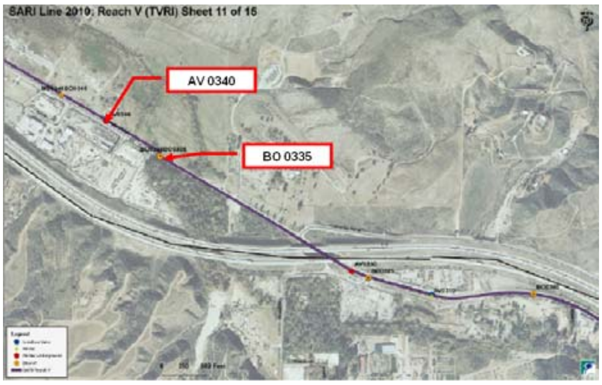


Figure 1. Location of measurement and blowoff sites

(a) AV 0340 (b) BO 0335

Figure 2. Manhole of AV 0340 and BO 0335

Figure 3. Blowoff hose connection and water tank truck

Figure 4. Data acquisition system for piezoelectric accelerometers

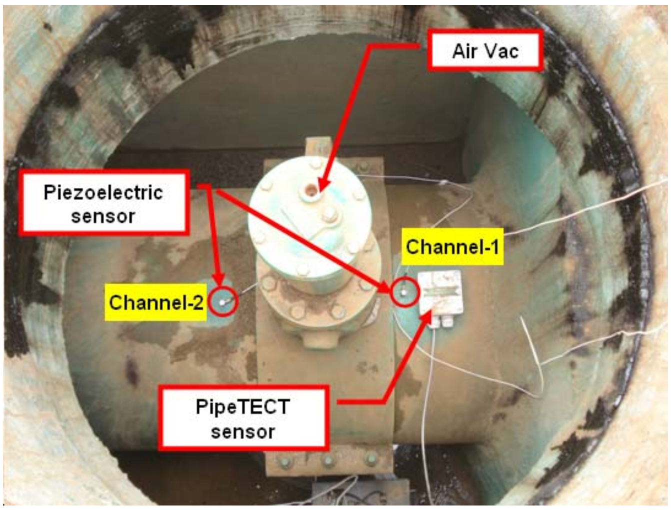


Figure 5. Installation of piezoelectric accelerometers

2.2 Metal pipe test

Another field test was performed at one site of the Irvine Ranch Water District (IRWD) near Rattlesnake Reservoir in Irvine, California on June 10, 2010. As shown in Figure 7, some parts of the buried water pipeline are exposed above the ground for control purposes. UCI team installed accelerometers on the pipeline with the cooperation by IRWD. The water flows from Irvine Lake to Rattlesnake Reservoir. The water pipe is made of metal and pressure change is expected to easily propagate from the control valve (refer the right-upper box in Figure 7) to adjacent measurement points. In this test, water pressure changes were incurred by opening and closing a control valve. Though the valve opening and closing should not be so rapid in order to protect the pipe system from potential damages due to sudden pressure changes, however, the pressure change was appropriately achieved as following the test procedure shown in Table 2.

During the entire test, the pipe vibration was recorded at three locations: (1) upstream, 7 m (23 ft) away from the control valve, (2) upstream near the control valve, and (3) downstream near the control valve. The sensor locations of (2) and (3) in Figure 7 were selected very next to the pressure gauges to correlate the pipe vibration with the water pressure change. The same accelerometers and data acquisition system used in PVC pipe test were used for this test. The same frequency of 1.25 kHz is thought to be enough to cover dominant frequency ranges of metal pipe.

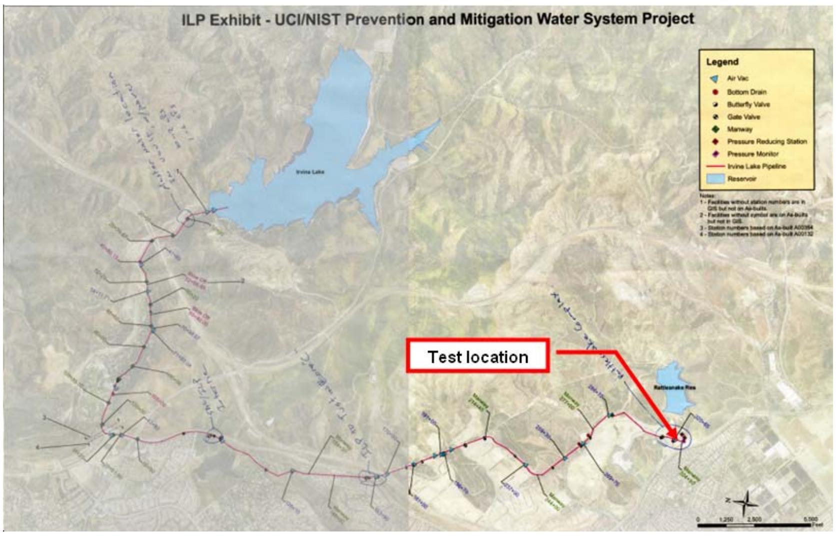


Figure 6. Map of IRWD pipeline in Irvine Lake and Rattlesnake area

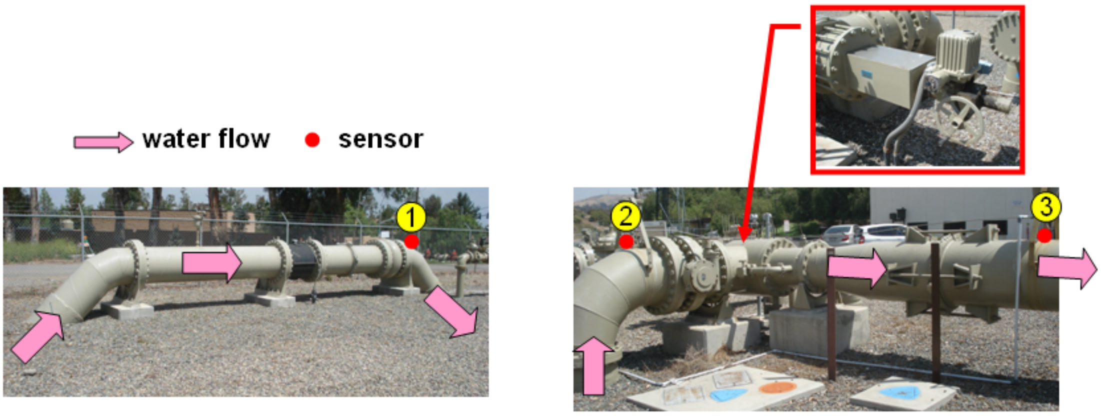


Figure 7. View of pipeline and sensor Locations

Figure 8. Sensor installation and pressure gages

Table 2. Test procedure for metal pipe

Valve state	Time (sec)	Description
Closed	0 – 205	
Begin of opening (B.O)	205	
Full opening (F.O)	375	20% pressure drop from closed state
Begin of closing (B.C)	914	
Full closing (F.C)	1,105	Pressure recovered to original state
End of test	1,500	Total time elapsed : 25 min

3. PVC PIPE DATA AND ANALYSIS RESULTS

3.1 Time domain

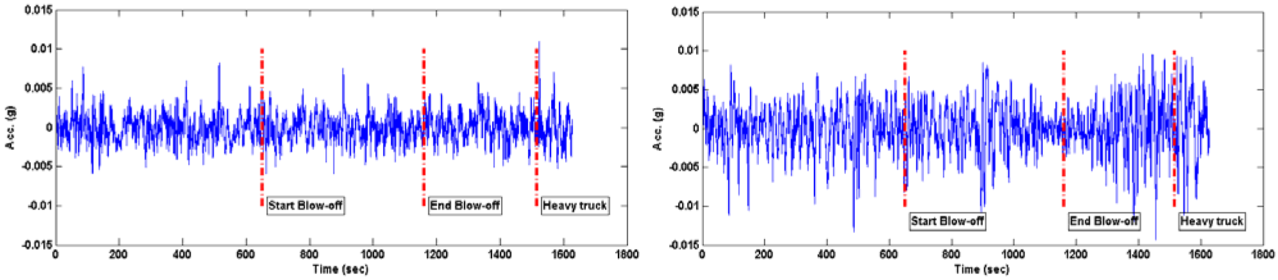
Figure 9 shows the recorded acceleration data from the accelerometers. The start and end time of the blowoff are marked with red lines on the figures. From the comparison of the acceleration amplitudes from channel 1 and 2, it is clearly seen that the existing airvac affects on the acceleration amplitude. The acceleration amplitude variation of channel 2 which is located after the airvac is wider than that of channel 1. Using the root mean square (RMS) of each signal, the effect of airvac is quantified. The RMS is calculated by Equation (1), where N is the total number of time steps of the recorded acceleration data and $\ddot{x}(t_i)$ is the recorded acceleration at time t_i .

The RMS value is 2.443 and 4.379 for channel 1 and 2, respectively. Based on this observation, it is recognized that the Airvac disturbed the flow and increased the average power level by two times the original flow. This kind of signal amplification by existing facilities should be considered in damage identification of rupture or leakage utilizing measured pipe vibration data.

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\ddot{x}(t_i)\right]^2} \tag{1}$$

During the test, there was a heavy truck passing by close to the measurement point, which provided extra information about the effect of ambient excitation on the pipe vibration. The truck passed by at around 1,515 seconds after the measurement start. The signal from channel 1 (refer to Figure 9 (a)) shows a clear peak at that moment, however, it is unknown whether the peak was caused by the heavy truck or not since there are many other apparent peaks of which peaks has almost the same amplitude before the event. Furthermore, there’s no significant peak in the signal of channel 2 (refer to Figure 9 (b)). So it is concluded that the effect of passing vehicles on the pipe vibration was not so apparent during the test. However, for some pipes buried not so deep, unknown excitation sources such as operating machines, road traffic, and hydraulic impacts from other pipe branches may significantly affect on pipe vibration.

From the all observations in time domain, it is hard to identify the water pressure drop by the blowoff of this pilot test. It is thought to be attributed to several reasons: i) the water pressure drop by the blowoff was so small considering the pipe diameter that the impact wave decayed rapidly, ii) because of the high damping characteristics of the PVC pipe, the generated impact wave decayed so fast during the propagation, as reported by many previous research.



(a) Channel 1 (b) Channel 2

Figure 9. Recorded acceleration from PVC pipe test

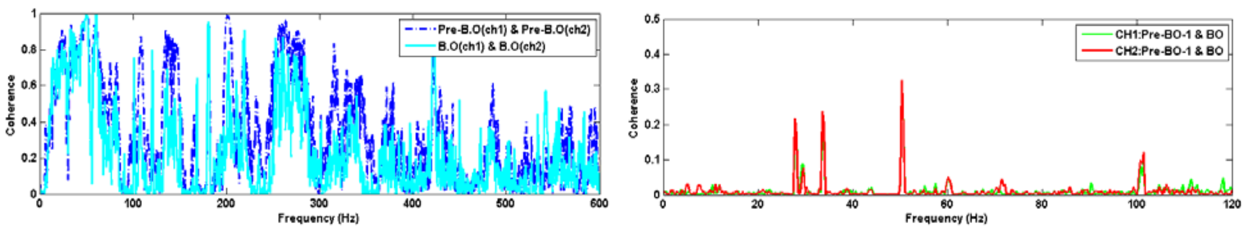
3.2 Frequency domain

To investigate correlation between pipe vibration and pressure drop, the recorded data are analyzed in the frequency domain also. The frequency characteristics of the pipe vibration before and during the blowoff are represented in terms of frequency contents change in frequency domain. First, the correlation of the recorded signals was analyzed using coherence function shown in Equation (2).

$$\gamma_{xy}^2(f) = \frac{|S_{xy}(f)|^2}{S_{xx}(f)S_{yy}(f)} \qquad 0 \le \gamma_{xy}^2(f) \le 1 \tag{2}$$

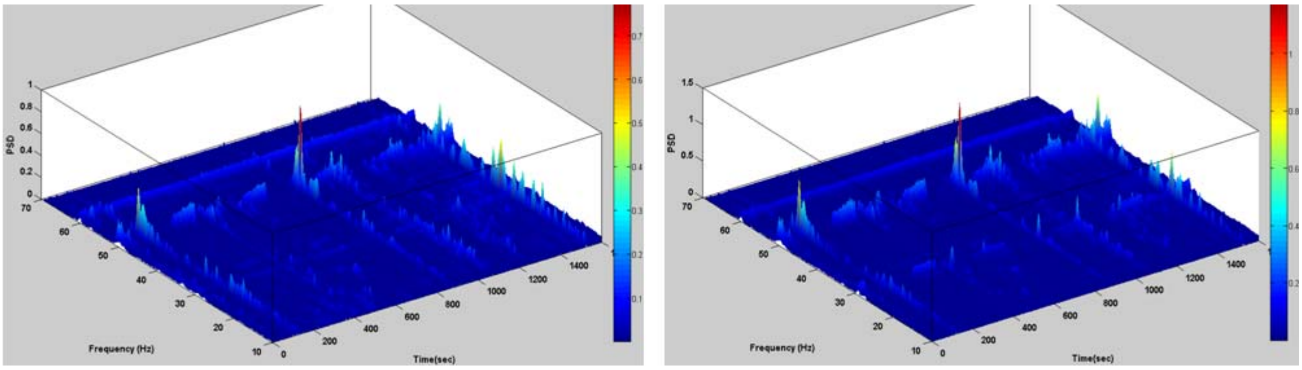
where, $S_{xx}(f)$ and $S_{yy}(f)$ are autospectral density function of signal x and y respectively; $S_{xy}(f)$ is cross-spectral density function of signal x and y. In actual practice, when the coherence function is near zero, two signals are not correlated.

Figure 10 (a) shows coherence functions between two signals for the pre- and during the blowoff periods, which indicate a good correlation between both signals. Especially, the coherence function values are high in the frequency range of 10-100 Hz. This frequency range is selected for detail analysis. The coherence functions of pre-blowoff (10~310 sec.) and during the blowoff (700 ~ 1000 seconds) within one signal are computed and plotted in Figure 10 (b). In the figure, the coherence functions are almost zero for most of the frequencies, except at several frequencies, which indicates that those frequency contents exist before and during the blowoff. For the time-frequency data analysis, the Short Time Fourier Transform (STFT) technique is adopted. For the STFT, a moving window length of 3.28 seconds (equal to 4096 data points) is chosen and the Hanning window with overlap ratio of 0.5 is adopted. Figure 11 shows the STFT results of the signals from the piezoelectric sensors. As seen in the figures, the peak at 60 Hz continues from the beginning of the recording, however, the peaks at 30 and 50Hz are repeated discontinuously for some periods and they are thought coming from a neighboring factory. No apparent frequency shift due to the blowoff is observed from this test.



(a) Between two signals (b) Within one signal

Figure 10. Coherence function



(a) Channel 1 (b) Channel 2

Figure 11. STFT of recorded signals

4. METAL PIPE DATA AND ANALYSIS RESULTS

4.1 Time domain

To correlate the acceleration data with water pressure change, the water pressure was monitored every 10 seconds automatically at two sensor locations. Pressure reading was done at every 30 seconds manually during the whole test and is plotted in Figure 12. The water pressure at the upstream (*refer sensor location (2) in Figure 7*) was 197 psi before the valve opening and it gradually dropped to 175 psi due to the valve transition to opening. The water pressure kept remaining at nearly a constant value during the full open state and then it recovered to the original pressure value by the valve closing. On the contrary to the upstream pressure, the water pressure at the downstream varied very little, remaining at around 48 psi during the whole test.

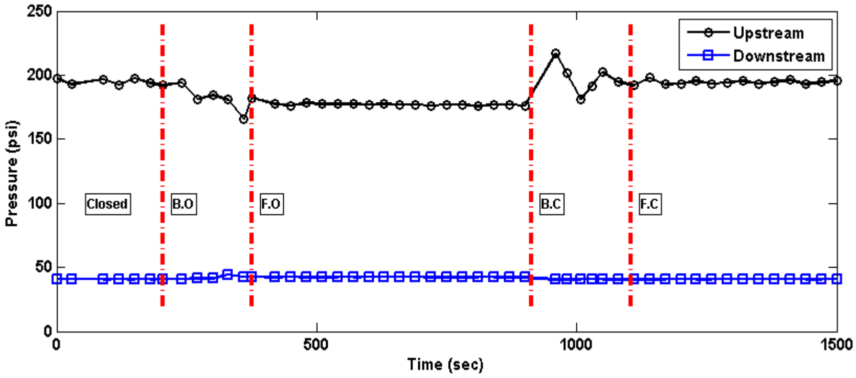
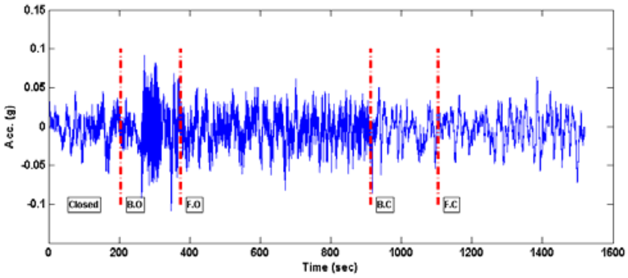
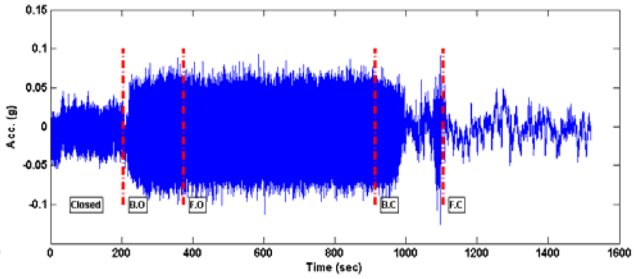


Figure 12. Water Pressure Change During Test

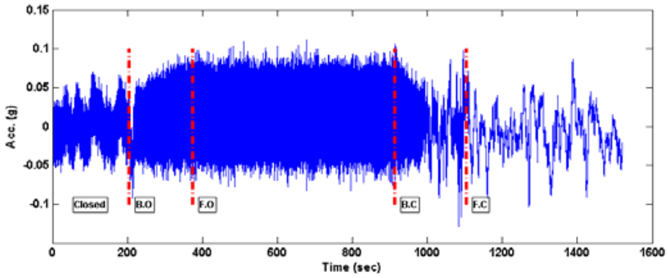
Figure 13 shows the recorded acceleration responses at each sensor location. In Figure 13 (a) of the recorded signal at the sensor location (1), it is clearly seen that during the first valve transition (200sec to 380sec) period, the acceleration amplitude becomes nearly two times greater than that of the close state. However, the sudden change in amplitude does not happen during the second valve transition from open to close state, in which the water pressure was recovered to the original value. Figure 13 (b) and (c) show the recorded acceleration time histories at the sensor location (2) and (3), which correspond to upstream and downstream respectively. The figures show that the acceleration amplitude during the open state is two times greater than that of the close state. It is attributed to the water turbulence near the valve created by controlling the valve. From the recorded data the pressure change is obviously detected during the transition and especially at Full Closing (F.C) the acceleration amplitude suddenly increased.



(a) Channel 1: upstream



(b) Channel 2: upstream



(c) Channel 3: downstream

Figure 13. Measured acceleration signal

4.2 Frequency domain

For the time-frequency analysis, the STFT technique is applied to the acceleration data recorded by the piezoelectric sensors. The time window length for the STFT was taken as about 4 seconds (4,096 data points) with overlap ratio of 0.5. Figures 14 and 15 show the STFT result of each signal. From each figure, the valve transition events are clearly differentiated around 200 and 1,100 seconds. In Figure 14 (b), a clear frequency shift is observed. The dominant frequency before the valve opening was 306Hz and it was shifted to around 315Hz during the valve transition. After the valve closing, it returned to the original frequency. In this case, the pressure drop was also identified in the frequency domain.

5. CONCLUSIONS

From the two field tests and data analysis both in time domain and frequency domain, findings and conclusions are drawn as follow:

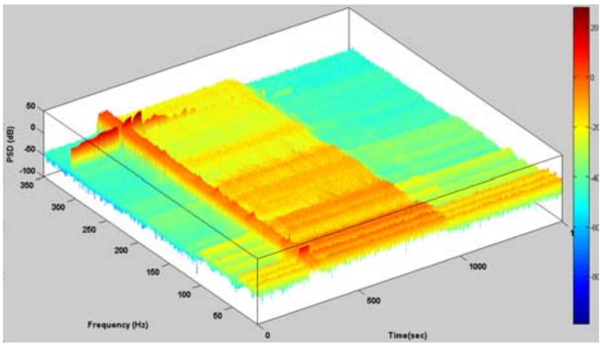
(1) The existing airvac perturbed the water flow and made the pipe vibrate more. The mean power of acceleration signal after the airvac was two times as the original signal. From this observation, the effects of existing facilities such as airvacs, valves, joints, and service connections on pipe vibration will be investigated in the future study.

(2) Depending on the pipe material, the minimum pressure drop and distance between sensor nodes deployed on pipeline network should be investigated for damage detection. The amount of pressure drop caused by rupture or leakage and the energy dissipation capacity of pipe material are major factors affecting the performance of the pipe damage detection.

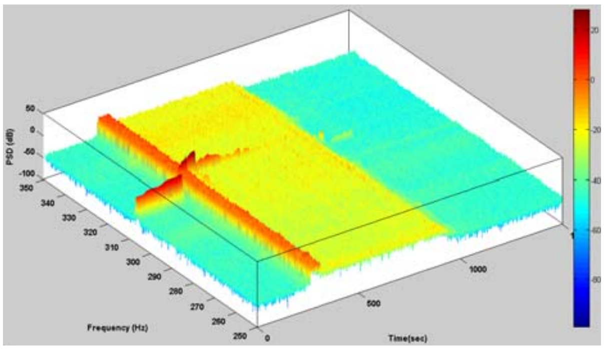
(3) Because pipe vibrates not only under rupture but also normal state, the nature of pipe vibration should be quantified in probabilistic sense to confidently discern abnormal pressure drops by rupture.

(4) In the metal pipe case, the pressure change was clearly detected from the acceleration signal. Though the amount of the pressure drop was only about 10%, the acceleration peak amplitude during the pressure drop was two times greater than that of the signal before pressure drop. The test results show that the acceleration amplitude change can be used as an indicator of abnormal pressure changes caused by rupture.

(5) In this test, the sensor locations were close to the pressure change location, i.e. the control valve. However, to validate the effectiveness of the proposed method, minimum distance between sensor nodes should be investigated to be deployed on pipe network.

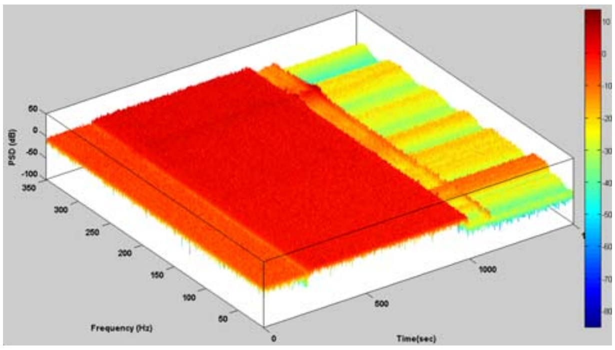


(a) Frequency range: 10~350 Hz

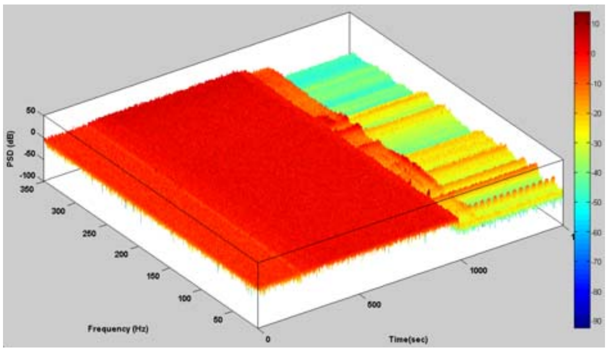


(b) Frequency range: 250~350 Hz

Figure 14. STFT of Channel 1



(a) Channel 2



(b) Channel 3

Figure 15. STFT of sensors

ACKNOWLEDGMENTS

This study was done under a National Institute of Standards and Technology (NIST) Technology Innovation Program (TIP) Grant 080058, as a joint venture with the Orange County Sanitation District (OCSD), Irvine RanchWater District (IRWD), Santa Ana Watershed Project Authority (SAWPA), and Earth Mechanics, Inc. Their support is immensely appreciated.

REFERENCES

[1] Fuchs, H.V. and Riehle, R., "Ten years of experience with leak detection by acoustic signal analysis," Applied Acoustics 33, 1−19 (1991).

[2] Hunaidi, O., Chu, W., Wang, A., Guan, W., "Detecting leaks in plastic pipes," Journal of American Water Works Association 92 (2), 82−94 (2000).

[3] Gao, Y., Brennan, M.J., Joseph, P.F., Muggleton, J.M., and Hunaidi, O., "A model of the correlation function of leak noise in buried plastic pipes," Journal of Sound and Vibration 277, 133−148 (2004).

[4] Yang, J., Wen,Y., and Li, P., "Leak location using blind system identification in water distribution pipelines," Journal of Sound and Vibration 310, 134−148 (2008).

[5] Gao, Y., Brennan, M.J., and Joseph, P.F., "A comparison of time delay estimators for the detection of leak noise signals in plastic water distribution pipes," Journal of Sound and Vibration 292, 552−570 (2006).